

## THE DEVELOPMENT AND DECAY OF THE 100-MB. SUMMERTIME ANTICYCLONE OVER SOUTHERN ASIA

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### ABSTRACT

The south Asian summer anticyclone is discussed with the aid of constant pressure charts, cross-sections, and graphs. The maximum anticyclonic circulation and the core of the subtropical easterly jet occurs close to the 100-mb. surface. Occasionally, this High migrates from its favored position over the Tibetan Plateau westward to the Caspian Sea. A Fourier analysis of the 100-mb. heights at 30° N. indicates that the longitudinal positioning of wave number one is a manifestation of the Asian anticyclone. An attempt to relate the appearance and variations in the surface southwest monsoon with the development of the high-level summertime circulation suggests that a direct vertical relationship is not straightforward and further study is needed to determine the exact nature of the linkage.

### 1. INTRODUCTION

From early times, men have written about the remarkable seasonal variation of the winds over southern Asia. In 326 B.C., the Greek naval commander Nearchus wrote that the northeast monsoon would be an aid to his return voyage from India to the Persian Gulf. Since then the surface aspects of the monsoons and the rainfall associated with them have been extensively documented. However, it was not until 1950 A.D. that the first mean upper wind charts (10–20 km.) for India and the surrounding neighborhood were presented by Venkiteshwaran [17]. These were the first charts to show that a wide belt of easterlies exists in the high troposphere and stratosphere over India during the summer months.

Since the discovery of the summer easterlies, an increasing amount of research has been initiated to determine their relationship to the low-level southwest (SW) monsoon over southern Asia. Sutcliffe and Bannon [12] indicate that the stratospheric easterlies over Aden (12°49' N., 45°02' E.) are established before the onset of the SW monsoon over India. Koteswaram and George [6] reveal that during the SW monsoon season the formation of depressions over the north and central parts of the Bay of Bengal and occasionally over the Arabian Sea is associated with perturbations in the high-level easterlies. More recently the existence of a summertime easterly current that reaches jet speeds over this area, between 150 and 100 mb., has been verified by Koteswaram [7].

This easterly jet flows along the southern boundary of an immense anticyclonic circulation. Crutcher [3] shows that during periods of maximum summertime development this high pressure system is centered over the Great Central Highlands of Asia (fig. 1). Its typical

shape is nearly elliptical, with a ridge line paralleling the east-west axis of the Great Central Highlands. Many times during the summer, this ridge line stretches from the Atlantic coast of northwestern Africa eastward to the western Pacific Ocean. At 100 mb., the broad stream of jet-speed easterlies to the south of this ridge line extends nearly to the equator while in middle latitudes over Asia there are strong westerlies.

Prior to the IGY, the scarcity of upper-air data in the region north of the center of this anticyclone hindered a comprehensive study of the westerly winds in the upper troposphere and stratosphere. However our knowledge of the circulation over this part of the world has been greatly enhanced by the recent expansion of the upper-air program in the region and by the publication of a paper [11] reviewing recent studies of the general circulation over eastern Asia. In this review, the circulation patterns from the surface to the tropopause for both winter and summer are described.

During the IGY-IGC period, the member nations of the World Meteorological Organization endeavored to increase the height and quality of radiosonde observations. The success of this endeavor has been demonstrated by the great improvement in the coverage and accuracy of analyses of the circulation at surfaces from 100 mb. up to 10 mb.

The Stratospheric Meteorology Research Project of the U.S. Weather Bureau has prepared for publication a series of daily 100-mb. and 50-mb. and three-times-monthly 30-mb. synoptic weather maps [15] for each month from July 1957 to June 1959. These maps are the principal source of data for the following discussion on the development and decay of the summertime 100-mb. anticyclone over southern Asia.

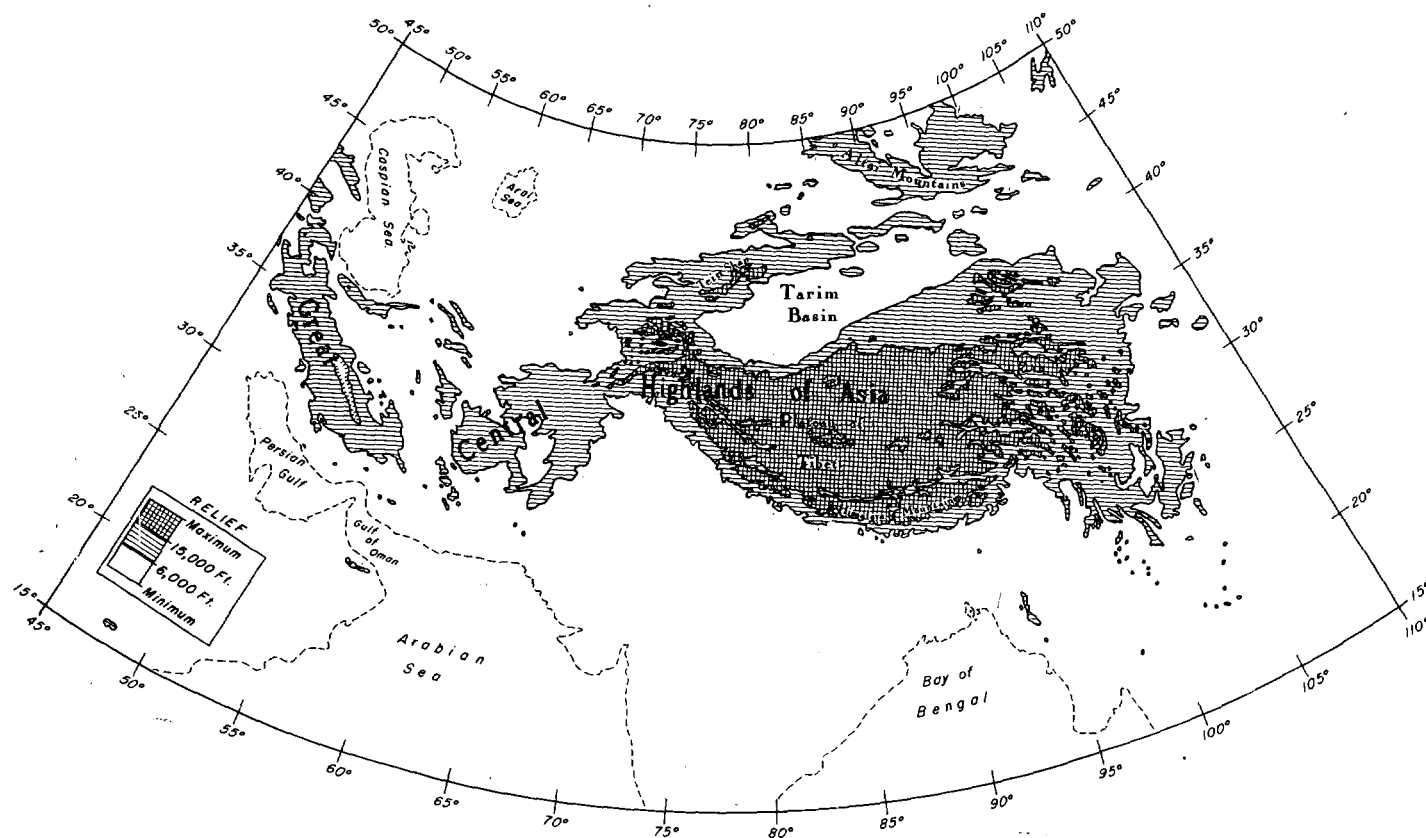


FIGURE 1.—Topography of southern Asia.

## 2. DEVELOPMENT OF THE 100-MB. ANTICYCLONE IN 1958

The 100-mb circulation over Asia during the 1957–58 winter was mainly westerly but less subject to waves of large amplitude than its counterpart in other longitudes. At times when long-wave perturbations of middle latitudes amplified, troughs penetrated far southward completely dissipating segments of the weak easterly belt circling the globe between 10° N. and the equator. In late April 1958, the initial development of the anticyclonic circulation occurred as the subtropical high pressure belt moved north and neared 20° N.

The anticyclone slowly intensified as it advanced northward over southeastern Asia, and by early June, easterly winds near 13° N., to the south of this high center, occasionally reached 50 kt. Upon reaching 27° N. the high center moved irregularly westward to a position over India by the middle of June. In the second half of that month, the band of jet-speed easterly winds broadened to cover the latitude band from 5° to 20° N. with speeds up to 100 kt. reported near 15° N. over India. Meanwhile, the 100-mb. High continued its expansion to include most of southern Asia and gradually developed a nearly elliptical shape typical of the summer season. The band of westerly winds at 100 mb. to the north of this High also shifted northward, so that by the end of June the maximum west

wind belt was located near the northern boundary of the Tibetan Plateau.

It is during the April to June period of development and intensification of the 100-mb. anticyclone that the SW monsoon annually sets in over southern Asia. The monsoon first develops in the Thailand region and then, two to three weeks later, appears over the Bay of Bengal and India as a “burst”; early June is the normal arrival date of the SW monsoon over southern India.

Attempts to correlate features of the high-altitude easterlies with those of the SW monsoon [12, 6, 7] have met with varying degrees of success. Koteswaram [7] has shown that the areas of vertical motion associated with the entrance and exit zones (acceleration and deceleration) of this high-altitude easterly jet appear well correlated with the mean rainfall distribution over southern Asia and northern Africa.

The circumstances leading to the “burst” of the monsoon over India in 1958 were very similar to those in the case study presented by Koteswaram [7] for 1955. Starting June 12 the intertropical convergence zone (ITC), at 1.5 km., advanced from Ceylon to northern India by June 22 [9], which coincided with the arrival of the maximum high-level easterly winds from the Thailand region to India. However, in 1959 the SW monsoon moved northward from Ceylon on about May 29. In this year the 100-mb. maximum easterlies did not appear over India as

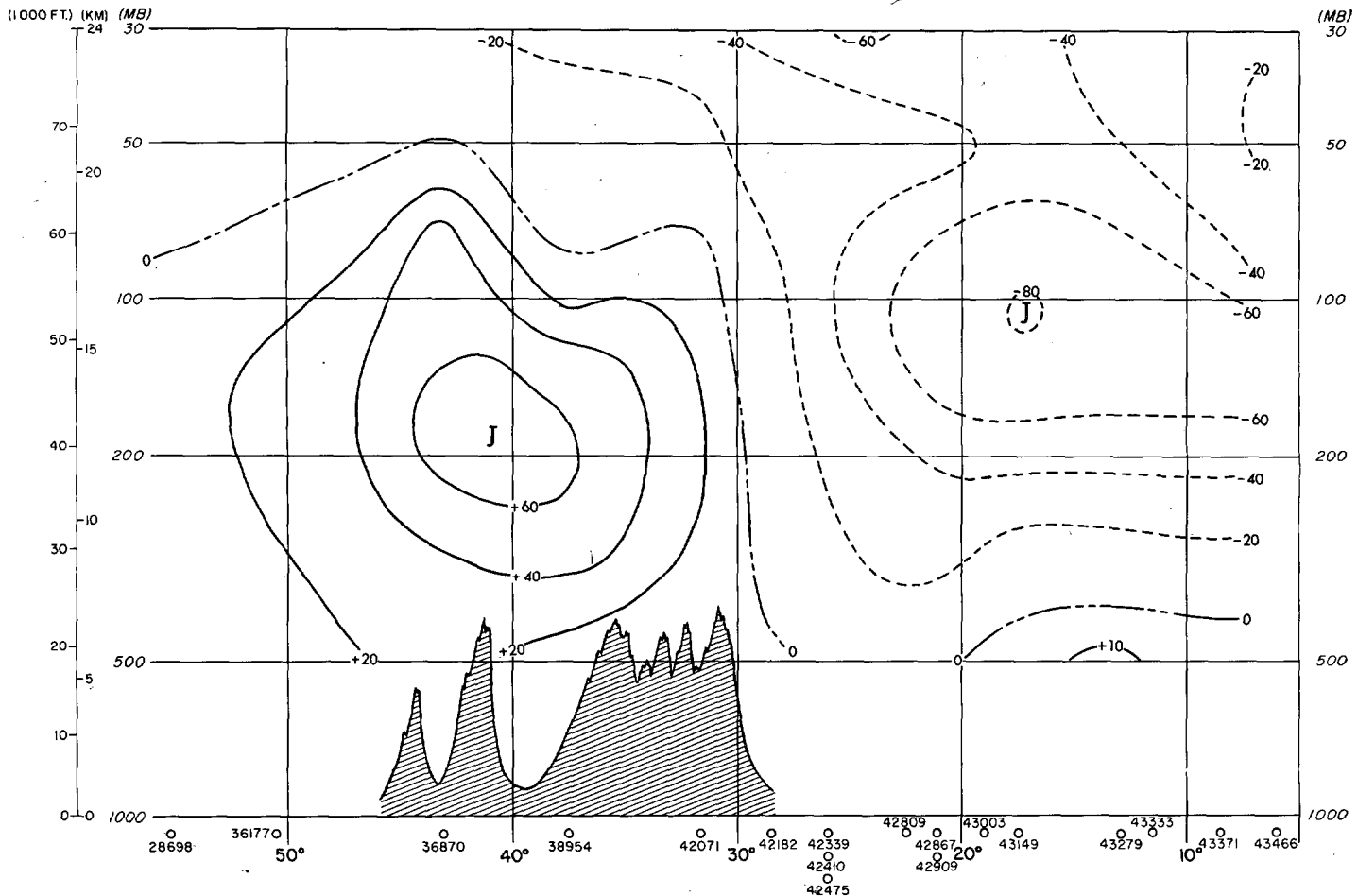


FIGURE 2.—East (dashed lines) and west (solid lines) wind components (kt.) along 80° E. for July 1957. Data sources included [16], microcards of IGY data, and wind components taken from [15].

the result of a sudden advance from Thailand, but gradually increased in intensity as the Asian anticyclone developed near 80° E., instead of in the more easterly position of the previous year.

### 3. THE SUMMER CIRCULATION

The anticyclonic circulation at 100 mb. reaches its greatest intensity during the months of July and August. This period also coincides with the time of maximum development of the SW monsoon of the lower troposphere and maximum development of the subtropical easterly jet stream.

The general synoptic conditions at the height of summer-time development were well represented in July 1957. A vertical cross-section at 80° E. (fig. 2) shows an easterly jet core of 80 kt. just below 100 mb. at approximately 17° N. At 100 mb. the easterly winds tended to accelerate from the southeastern coast of Asia into a zonal current of maximum winds across India and then decelerated as they approached Africa. This wind belt was subject to extensive fluctuations in position and intensity as may be seen by reference to daily 100-mb. charts for July 26, 28, 30, 1957 (fig. 3). According to the movement of the 100-kt.

isotach analyzed on these charts, the jet maximum in the easterlies advanced westward across southern Asia at 28 kt.

From the daily map series [15], data indicate that maximum values of anticyclonic shear periodically tend to exceed the Coriolis parameter, especially during periods of strong winds and with southward shifts of the maximum wind belt. Whether this effect is real or just a manifestation of instrument error cannot be determined, so the analyst adjusted the contour spacing to prohibit negative absolute vorticity in the geostrophic winds. However, values of negative absolute vorticity have been measured in other, but rare, cases of tropical easterly jets. Alaka [1] shows that a narrow band of negative absolute vorticity in the tropical easterly jet can exist during periods of maximum development. From figure 8 the mean anticyclonic shear at 24° N. over India measures 75 percent of the Coriolis parameter and may measure higher in view of the previously mentioned adjustment of contours.

The westerly flow through the 80° E. meridian (fig. 2) has its maximum in summer near 41° N. with a speed of about 70 kt. at or just above 200 mb. Pogorian [10] states that the northward movement of the jet stream in spring coincides with the appearance of a closed low pressure sur-

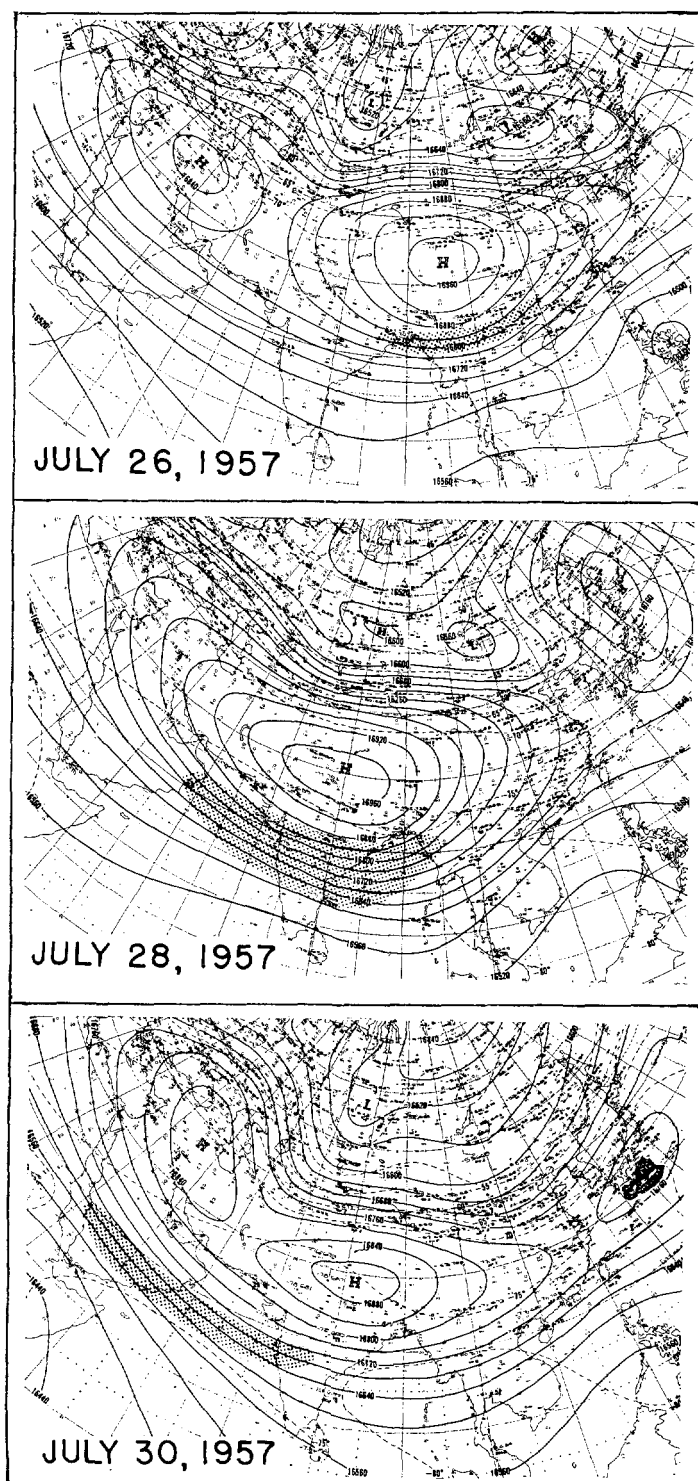


FIGURE 3.—100-mb. charts, contours labeled in meters, isotherms in ° C. Shaded area includes region of chart where the geostrophic wind exceeds 100 kt. (from [15]).

face region over northern India and therefore the movement is connected with the formation of the south Asiatic summer depression.

Accurate description of the tropopause level and cor-

responding temperature field over southern Asia is made difficult by the scarcity of reliable data at or above the tropopause level in lower latitudes. The tropopause presented here (fig. 4) is not in complete agreement with those inferred from the charts presented by other authors [7, 11, 2]. Such differences probably reflect the year-to-year variation in the summer season, but may also be the result of increased data and different interpretations of the data.

South of 30° N., the Asian tropical tropopause, in July 1957, had a mean position at about 90 mb. with an apparent maximum elevation just south of the center of the 100-mb. anticyclone. Usually the temperature minimum is found at the highest point of the tropopause and, from figure 4, the lowest mean temperature ( $-77^{\circ}$  C.) was located at the peak. However the paucity of soundings penetrating the tropical tropopause in this region makes its analysis very subjective. In addition, the data revealed many inconsistencies in that the tropopause level varied from 135 to 65 mb. and its temperature from  $-65^{\circ}$  to  $-85^{\circ}$  C.

The equatorial tropopause can be traced northward into the middle-latitude stratosphere, becoming more diffuse until it finally disappeared. Multiple tropopauses are thus characteristic of soundings in the region near 40° N.

Meridional differences between the mean conditions over the two largest land masses of the Northern Hemisphere are depicted in figures 5 and 6. Both of the selected longitudes (100° W. and 80° E.) traverse the area of maximum 100-mb. height values. Figure 5 shows the differences between the zonal wind components at 80° E. (fig. 2) and 100° W. (fig. 7). The large easterly component of  $-60$  kt. near 18° N. is due to the presence of the easterly jet across India and the absence of such a jet across Cuba and Mexico. In middle latitudes large positive and negative values are mainly a consequence of the lower and more northerly position of the westerly jet across North America.

Figure 6 shows how the temperature conditions differ

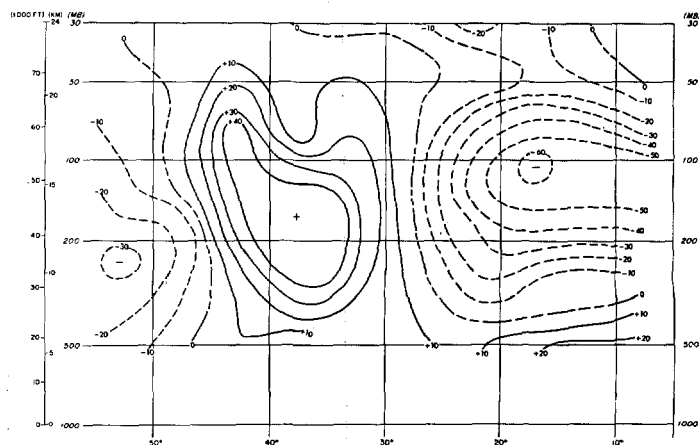


FIGURE 5.—Difference in east-west wind component (in kt.) along 80° E. and 100° W. for July 1957. Negative values indicate greater east wind component at 80° E. Positive values indicate greater west wind component at 80° E.

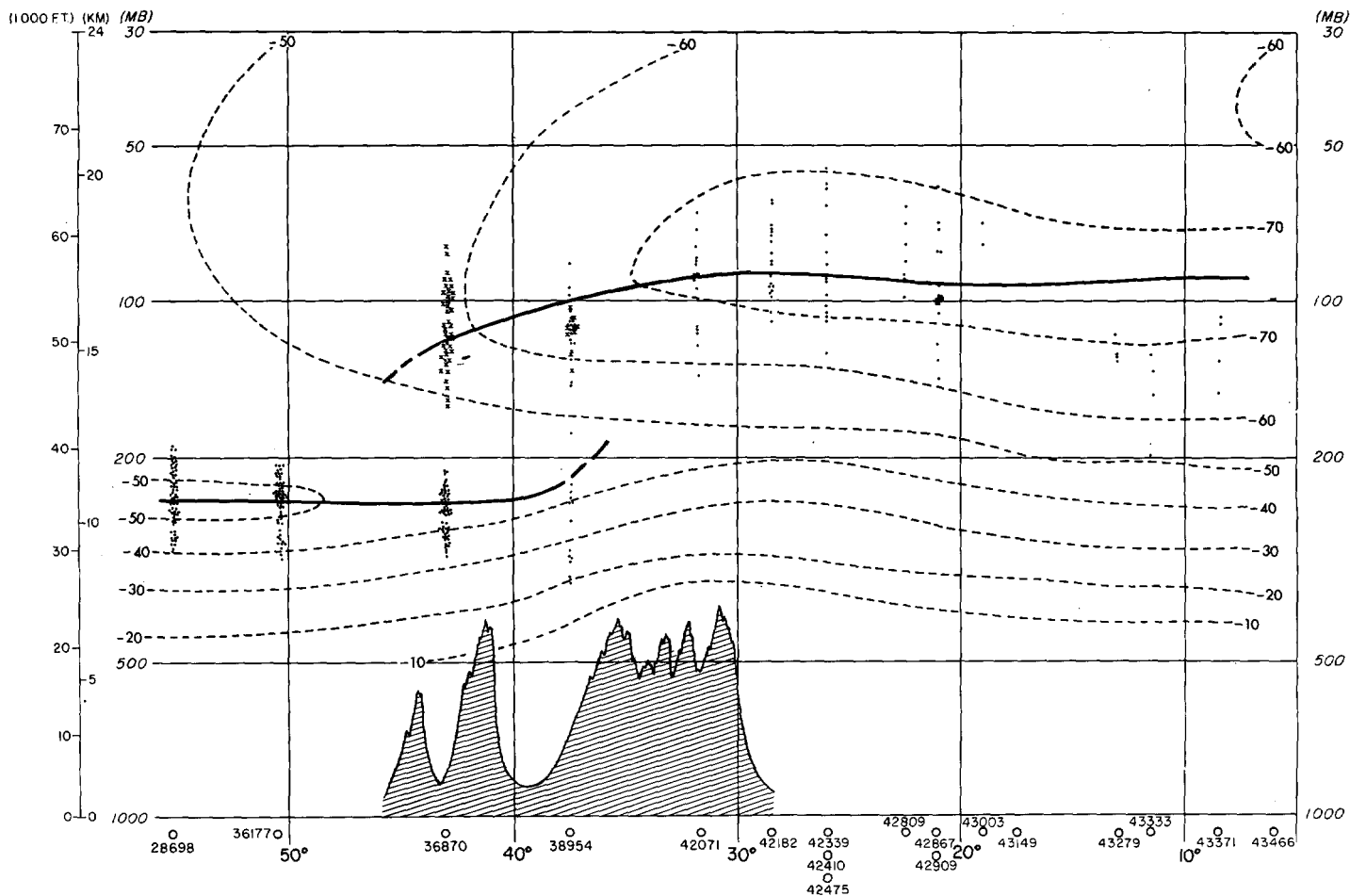


FIGURE 4.—Temperature-tropopause profile along 80° E. for July 1957. Dots indicate first tropopause level reported; X's indicate higher levels at stations reporting multiple tropopauses. Data sources include [15], [16] and microcards of IGY data.

above the two land masses of unequal size and different topography. The relatively warm air (positive values) that extends to above 150 mb. over northern India and Tibet may be ascribed to several causes. The warm air over northern India may be largely due to the release of

latent heat of condensation from the SW monsoon, while over the Himalayas and the Tibetan Plateau the principal cause may be the convective transport of air heated by solar radiation incident upon the high terrain.

Above this warm layer, there is a compensating layer

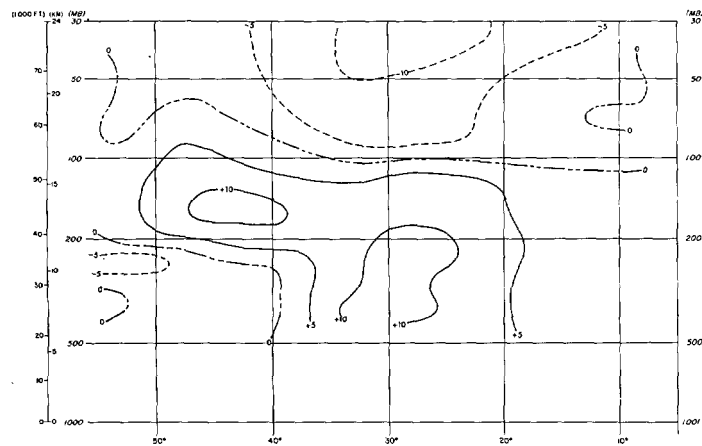


FIGURE 6.—Difference of temperatures (in °C.) between 80° E. and 100° W. for July 1957. Positive values indicate higher temperature at 80° E. Temperature profile for 100° W. is not presented in paper.

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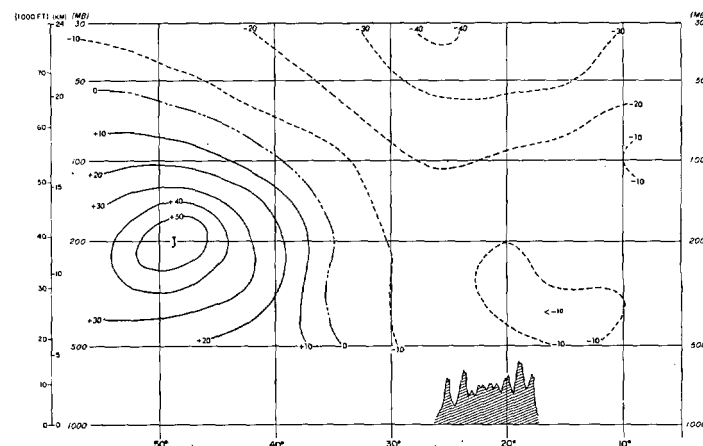
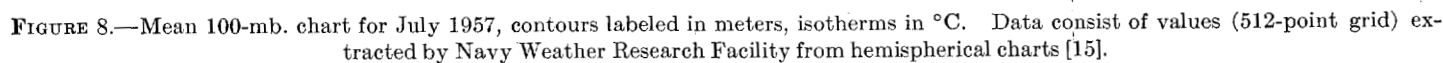


FIGURE 7.—East (dashed lines) and west (solid lines) wind components (kt.) at 100° W. for July 1957. Data sources include [15], [16], and microcards of IGY data.



During July 1957, the mean Asian High had a position

Assuming no variation in the analyses and accuracy of

data, figure 9B indicates that the 100-mb. surface was about 60 m. higher in 1958 when it shifted westward off the Tibetan Plateau than in the previous year. This shift of the High to area 1 from area 2 is partially attributed to its migration westward to the Caspian Sea on July 17, 1958 (fig. 10). During such displacements the north-easterly flow, normally found along the China coast, occurred directly over the Tibetan Plateau. However, it is borne out by examination of the 100-mb. charts that when troughs displaced the high center from the Tibetan Plateau, the 100-mb. height of this region equaled or exceeded the high centers in other parts of the world. This supports the discussion by Flohn [4, 5] and Koteswaram [7, 8] that the troposphere receives heat from the relatively warm, elevated Tibetan Plateau.

Some results of a Fourier analysis of the 100-mb. heights by Teweles [13], along several latitude circles

FIGURE 9.—Frequency distribution by area, of the 1200 GMT, 100-mb., 16,960 gpm. contour, for July 1957–58. (A) Areas 1, 2, 3; (B) Stippled columns of frequency graph correspond to areas in (A). Mutually inclusive events were recorded in each area.

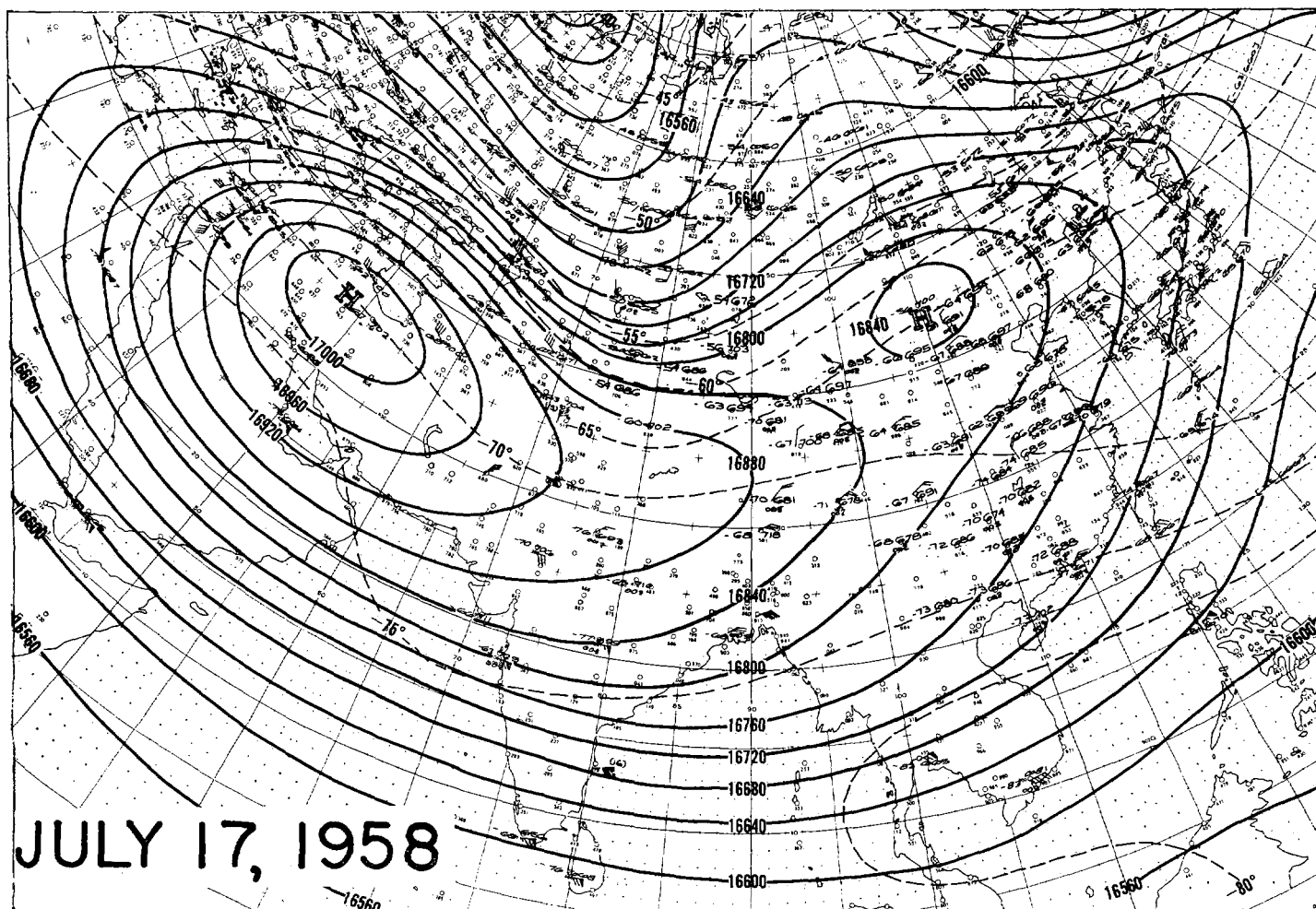
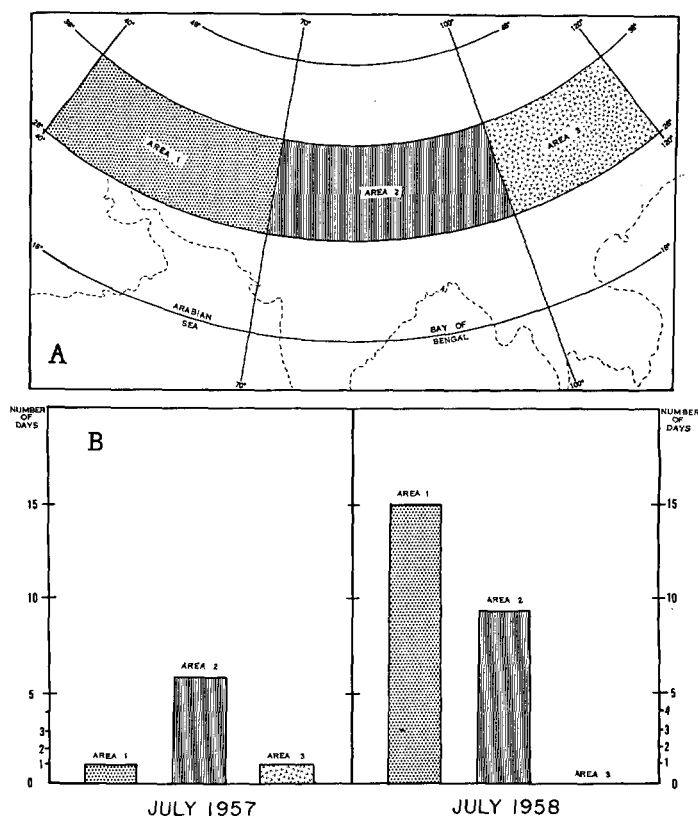


FIGURE 10.—Section of 100-mb. chart for July 17, 1958, contours labeled in meters, isotherms in °C. (from [15]).



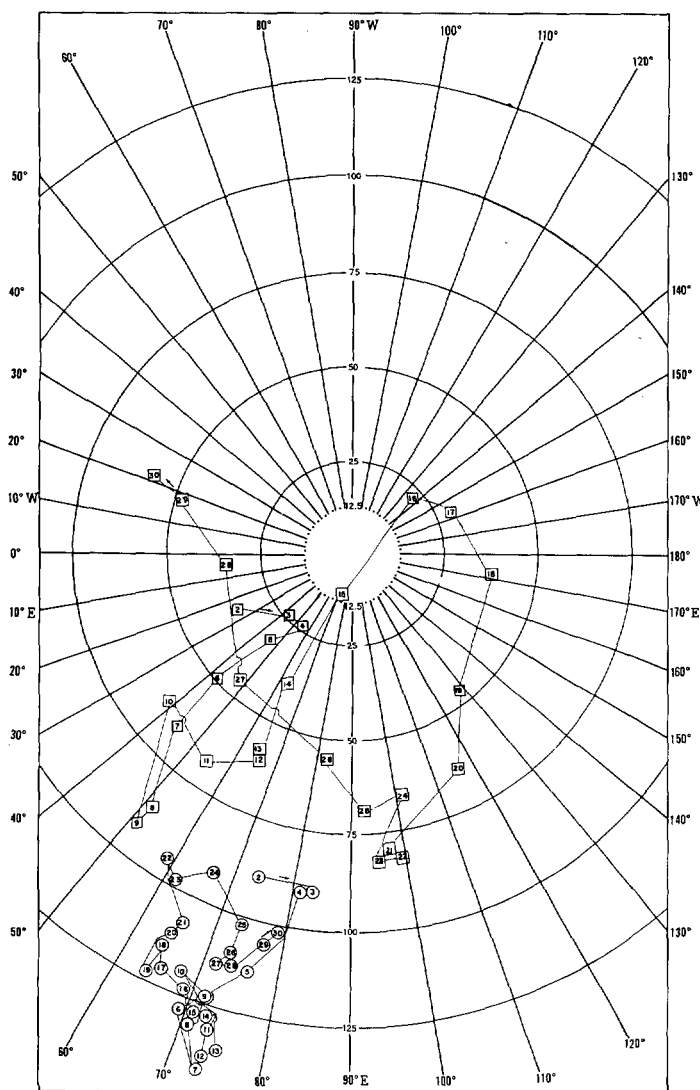


FIGURE 11.—100-mb. smoothed (3-day running means) daily angular positions ( $^{\circ}$  long.) and amplitude (meters) of wave number one ridge for July 1957. Squares indicate daily positions at  $70^{\circ}$  N. and circles daily positions at  $30^{\circ}$  N. Fourier analysis was performed by "Partition of Atmospheric Energy" computer program developed by Saltzman and Fleisher of Massachusetts Institute of Technology. Computer input consists of 100-mb. grid-point data extracted by the Navy Weather Research Facility from hemispherical charts (from [13]).

for July 1957 are shown in figures 11 and 12. At  $30^{\circ}$  N., the large amplitude of stationary wave number one, with its ridge located near  $75^{\circ}$  E., is clearly a manifestation of the Asian anticyclone. The persistence of this circulation over the highlands of Asia in 1957 is reflected in the small daily changes in angular position of wave number one (fig. 11). At  $30^{\circ}$  N. daily ridge positions lie within a sector only  $20^{\circ}$  wide while at  $70^{\circ}$  N. the movement covers  $250^{\circ}$ , largely due to activity in the latter half of the month. However the monthly mean positions of the wave at  $30^{\circ}$  N. and  $70^{\circ}$  N. are at nearly the same longitude.

The tendency for a relatively weak anticyclonic cell to be located at 100 mb. over North America nearly  $180^{\circ}$

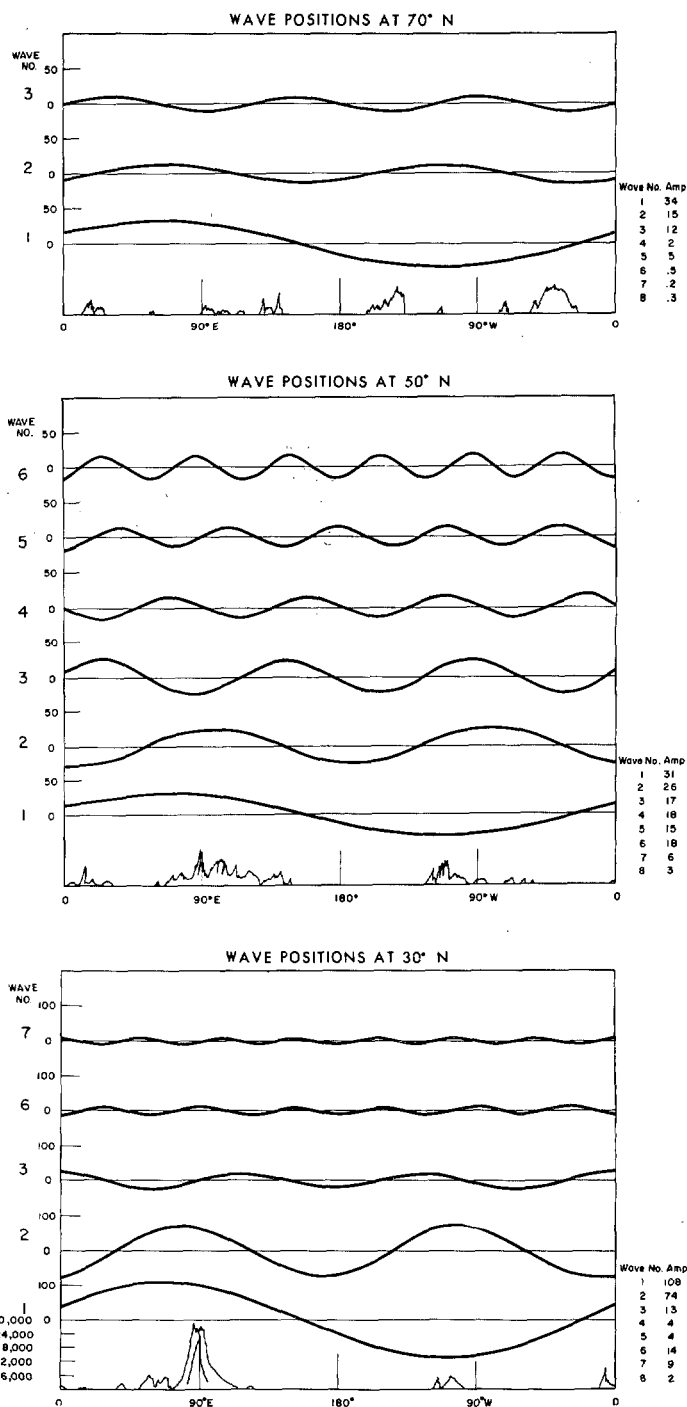


FIGURE 12.—100-mb. wave position ( $^{\circ}$  long.) and amplitude (meters) at  $30^{\circ}$ ,  $50^{\circ}$ , and  $70^{\circ}$  N. for July 1957. Note doubling of scale at  $30^{\circ}$  N. Fourier analysis as in figure 11.

longitude away from the Asian cell is manifested by stationary wave number two (fig. 12). Note also that its influence extends from  $30^{\circ}$  N. to  $70^{\circ}$  N., and that at  $50^{\circ}$  N. its amplitude is very nearly equal to that of stationary wave number one.

The amplitudes of stationary waves of a number larger than two tend to be quite small due either to lack of pre-



ferred position or to nonexistence of such waves. At  $50^{\circ}$  N., an interesting feature of this type of analysis is, however, shown by the "beat" in frequencies 4, 5, and 6 to produce a substantial short-wave trough at  $70^{\circ}$  W. in the mean height-contour chart (fig. 8). Other characteristics of the mean flow can be described in a like manner.

### 5. RETREAT AND DECAY OF THE 100-MB. HIGH OVER SOUTHERN ASIA

In the 100-mb. charts available for the autumn of 1957, the stages of the breakdown of the Asian High can be observed. From August 25 to 29 the High moved eastward, intensifying slightly upon reaching the eastern edge of the Tibetan Plateau. With continued eastward movement in the next two days, its central height decreased by about 160 m.

At about the same time, the easterly jet increased from 75 kt. on August 25 to 100 kt. on August 27. With the movement of the High, the area of maximum easterly winds directly south of the high center progressed eastward in the upstream direction. After August 29 the easterly jet appears to have weakened simultaneously with the decay of the High.

On September 7 a new center of anticyclonic circulation gradually appeared over the Tibetan Plateau replacing the High that had previously moved eastward. During the latter half of September, the High weakened as it meandered southward from the highlands area until at the end of the month it was located near  $27^{\circ}$  N. Synoptic charts for early October display the last traces of a distinct 100-mb. high center as it dissolved into the subtropical high pressure belt. The high pressure belt then retreated more rapidly southward and was below  $15^{\circ}$  N. by mid-October.

The 1958 breakdown occurred in the following manner. By the last week of August the High had broken into two cells, each with 100-mb. heights of 16,720 m. about  $45^{\circ}$  of longitude apart. One cell was located at the eastern edge of the Tibetan Plateau with the other near the Caspian Sea. During the first half of September, the eastern Tibetan Plateau cell weakened and disappeared, leaving the western cell as the predominant feature. By the 15th this High was at its maximum intensity with a central height of 16,880 m. and located just south of the Caspian Sea. After stagnating in this location for nearly one week, it moved rapidly eastward to a position over northern India and slowly weakened. For the remainder of the month the High hovered south of the Tibetan Plateau with 100-mb. heights about 60 m. higher than those of the previous year. Throughout September, the easterly winds over southern India maintained speeds of about 50–60 kt.

By the first week of October the Asian High had lost its identity within the subtropical high pressure belt. However, the high belt stayed at  $20^{\circ}$ – $25^{\circ}$  N. for the rest of the month maintaining higher 100-mb. values as in the latter half of September. Not until the first days of November, when a long-wave perturbation of the middle latitudes

amplified and advanced toward India, did the subtropical high pressure belt retreat farther southward to its winter-time position south of  $15^{\circ}$  N.

### 6. CONCLUSIONS

With the exception of the polar vortex itself, the Asian 100-mb. anticyclone is the most intense and persistent circulation found at this pressure surface over the Northern Hemisphere. Its influence extends from the Atlantic coast of Africa across southern Asia to the Pacific Ocean. A Fourier analysis of the 100-mb. heights at  $30^{\circ}$  N. shows that the longitudinal positioning of wave number one is a manifestation of the Asian anticyclone.

During July 1958, the High departed from the Tibetan Plateau for periods of one week or more indicating that outside forces can affect the position and intensity of this thermally driven High. There also appears to be considerable annual variation in the amount of zonal movement displayed by this High.

Above the warm tropospheric air that exists over the Tibetan Plateau and extreme northern India, the stratospheric air is relatively cold. This cold air is found mainly in the easterly flow of the middle stratosphere and accounts for the rapid dissipation of the anticyclone from 100 to about 50 mb.

Although the appearance of the SW monsoon is closely associated in time with the development of the summer-time circulation at 100 mb., further study is needed to determine the exact nature of the linkage between the SW monsoon, the easterly jet, and the developing south Asian High.

Only major aspects of the 100-mb. circulation could be described in this paper. For more detailed studies of the high atmosphere over southern Asia, improved rawinsonde observations are a principal requirement.

### ACKNOWLEDGMENTS

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